Sustainable earth-based vs. conventional construction systems in the Mediterranean climate: Experimental analysis of thermal performance

Sustainable earth-based vs. conventional construction systems in the Mediterranean climate: Experimental analysis of thermal performance

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Abstract. The building envelope has high potential to reduce the energy consumption of buildings according to the International Energy Agency (IEA) because it is involved along all the building process: design, construction, use, and end-of-life. The present study compares the thermal behavior of seven different building prototypes tested under Mediterranean climate: two of them were built with sustainable earth-based construction systems and the other five, with conventional brick construction systems. The tested earth-based construction systems consist of rammed earth walls and wooden green roofs, which have been adapted to contemporary requirements by reducing their thickness. In order to balance the thermal response, wooden insulation panels were placed in one of the earth prototypes. All building prototypes have the same inner dimensions and orientation, and they are fully monitored to register inner temperature and humidity, surface walls temperatures and temperatures inside walls. Furthermore, all building prototypes are equipped with a heat pump and an electricity meter to measure the electrical energy consumed to maintain a certain level of comfort. The experimentation was performed along a whole year by carrying out several experiments in free floating and controlled temperature conditions. This study aims at demonstrating that sustainable construction systems can behave similarly or even better than conventional ones under summer and winter conditions. Results show that thermal behavior is strongly penalized when rammed earth wall thickness is reduced. However, the addition of 6 cm of wooden insulation panels in the outer surface of the building prototype successfully improves the thermal response.

1. Introduction

The building sector represents 32% of total CO_2 emissions during operation phase. However, manufacturing of building materials should not be underestimated because they accounted around 13% of total world CO_2 emissions [[1]]. Due to the increasing environmental awareness in society, the interest in the use of sustainable building materials is also noticeable [[2]-[4]]. For this reason, the present study aims at adapting rammed earth construction system to current requirements [[5]] because of its interest regarding sustainability, recyclability, low price, wide availability, and low environmental cost, among others. Furthermore, the study is also focused on experimentally demonstrating under real weather

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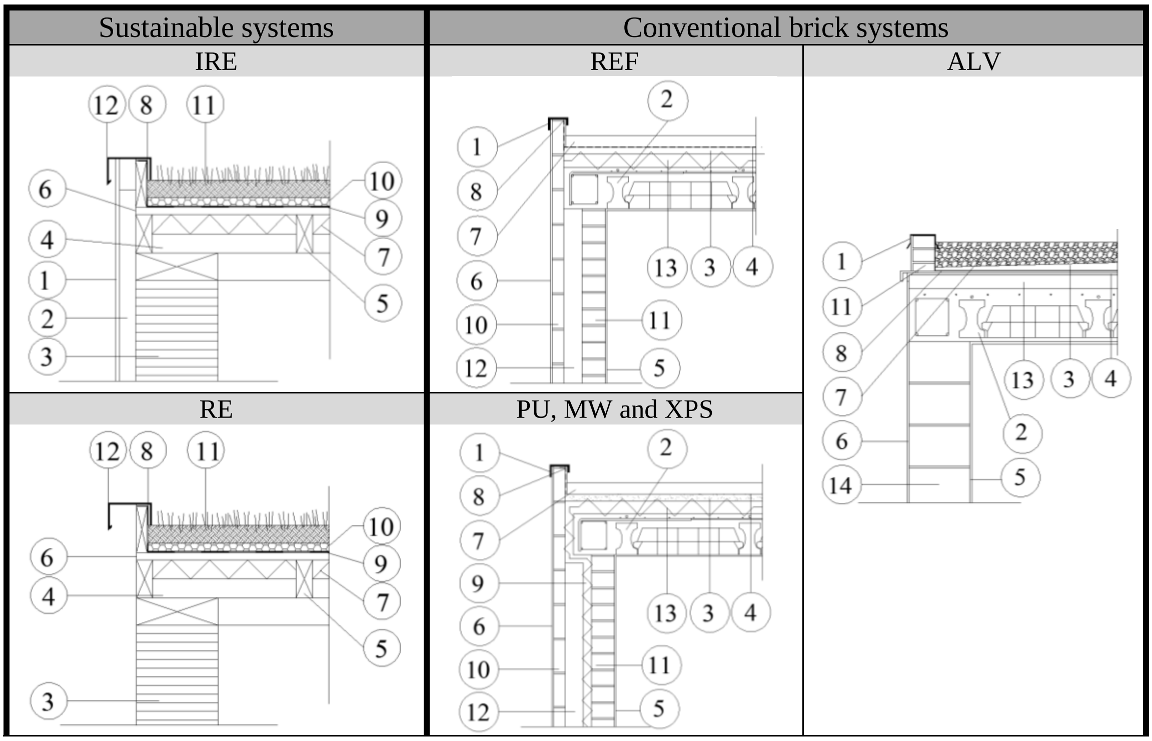
conditions that sustainable construction systems can thermally behave in a similar way than conventional ones.

2. Experimental set-up and methodology

Seven cubicles built in the set-up located in Puigverd de Lleida, Spain (Csa climate according to Köppen-Geiger climate classification [[6]]) were used along the experimentation. Two of them were built using sustainable construction systems based on the use of raw earth and wood, the other five cubicles were built using construction systems conventionally used in a Mediterranean climate based on reinforced concrete structure and clay brick walls. These five conventional construction systems were previously tested and evaluated in Cabeza et al. [[7]]. All cubicles have the same inner dimensions (2.4 x 2.4 x 2.4 m), orientation (N-S, 0º) and configuration (insulated metal door in the north wall and no windows). Each construction system is listed and illustrated below (Figure 1).

The key point in this research is to demonstrate that similar thermal behaviour can be achieved by adapting rammed earth to modern construction systems in summer [[8]] and winter conditions. To achieve this goal, rammed earth walls thickness has to be reduced (till 29 cm in this case) what means that it needs to be insulated in order to achieve a proper thermal behaviour [[9]] to be comparable to conventional construction systems:



1. Clay and straw coating 1.5 cm	1. Aluminium sheet 5 mm
2. Wooden insulation 6 cm Sylvactis	2. Concrete precast beam in 25 cm concrete slab
3. Rammed earth wall 29 cm	3. Cement mortar, roof slope 3%
4. Roof insulation 5 cm	4. Double asphaltic membrane
5. Wooden beams 6 x 14 cm	5. Gypsum coating
6. Wooden board 2.7 cm	6. Single layer mortar
7. Wooden strip 6 x 12 cm	7. Gravel
8. Waterproof sheet	8. Waterproof sheet
9. Geotextile sheet	9. Walls insulation 5 cm
10. Drainage layer 3 cm	10. Brick 7 cm
11. Substrate 6.5 cm	11. Brick 14 cm
12. Aluminium sheet 5 mm	12. Air chamber 14 cm
	13. Roof insulation 5 cm
	14. Alveolar brick 30 x 19 x 29 cm

Figure 1. Construction systems details

- RE (Non-insulated rammed earth): Load-bearing rammed earth walls of 29 cm (with ground humidity protection of 19 cm composed by one row of alveolar brick and a polypropylene waterproof sheet).
- IRE (Insulated rammed earth): Same construction system than RE but walls are insulated with natural wood fibres panels of 6 cm (SYLVACTIS 140 SD ITE) and 1 cm of natural coating based on clay and straw (thickness < 2 cm).
- REF (Reference): Gypsum, perforated bricks, air chamber, hollow bricks, and cement mortar coating. Structure made of 4 reinforced concrete pillars.
- PU (Polyurethane insulation): Same layer distribution than REF but with 5 cm of polyurethane sprayed foam between the perforated bricks and the air chamber.
- MW (Mineral wool insulation): Same layer distribution than REF but with 5 cm of mineral wool between the perforated bricks and the air chamber.
- XPS (Polystyrene insulation): Same layer distribution than REF but with 5 cm of extruded polystyrene.
- ALV (Alveolar bricks): Gypsum, alveolar bricks and cement mortar coating. Alveolar bricks act as bending walls.

Cubicles are fully monitored to register inner ambient temperature and humidity (using ELEKTRONIK EE21 at a height of 1.5 m with an accuracy of ±2 %) and surface wall temperatures (using calibrated Pt-100 DIN B sensors with error ±0.3 ºC which measure east, west, north, and south inner surface wall temperatures). Furthermore, each cubicle has a domestic heat pump (Fujitsu Inverter ASHA07LCC) to cover the heating and cooling demand. The electrical energy consumed by these heat pumps is measured with an electrical network analyser (Circutor MK-30-LCD).

Two types of experiments were carried out during summer 2015 and winter 2016:

- Free floating (heat pump not used).
- Controlled temperature (temperature set at 21ºC with the heat pump).

3. Results

Although significant testing periods were evaluated the authors have selected one representative week for each season (summer and winter) and experiment. It should be also mentioned that experiments were evaluated when inner temperature of cubicles were kept stable (transitory periods between experiments were discarded).

In Table 1, climatic data registered of the selected weeks are shown as average, maximum and minimum temperatures and humidity, thermal amplitude, average maximum solar radiation, and average solar radiation per day. The key point of the experimentation is to compare the energy performance of sustainable and conventional construction systems configurations under the different selected weather conditions.

Table 1. Climatology data in the selected weeks.

		Summer		Winter	
		15th-21st July Free floating	18th-24th June Set Point 21ºC	10th-16th February Free floating	8th-14th January Set Point 21ºC
T	[ºC]	27.3	24.0	10.9	10.5
T_{max}	[ºC]	38.8	33.1	16.8	16.9
T_{min}	[ºC]	17.4	15.2	7.4	3.7
Thermal amplitude	[ºC]	21.3	17.9	9.4	13.1
H	[%]	64	57	80	70
H_{max}	[%]	97	86	97	88
H_{min}	[%]	28	29	54	46
Rad_{max}	[W/m^2]	1,036	1,107	716	539
Solar radiation per day	[kWh/m^2 ·day]	91	105	31	25

3.1. Summer

Results obtained during the experimentation in free floating and controlled temperature conditions are shown in Figure 2. It can be noticed that, on one hand, two of the non-insulated cubicles (RE, REF and ALV) have the largest indoor temperature oscillations, showing temperature differences during day-night period between 2-3ºC in free floating conditions. RE cubicle showed the highest temperature oscillations, even higher than REF cubicle, while ALV cubicle presented temperature oscillations around 1.5ºC but always higher than insulated cubicles. Insulated cubicles (IRE, PU, MW and XPS) show similar temperature profiles with temperature differences less than 1ºC. On the other hand, in controlled temperature experiments (set point of 21ºC) the same behavior was observed when analyzing the accumulated electrical energy consumption in one week. Regarding non-insulated cubicles, RE cubicle consumed more electrical energy to maintain at 21ºC its inner ambient temperature than the REF cubicle but ALV cubicle consumed less energy than the REF. All insulated cubicles showed similar electrical energy consumptions in one week.

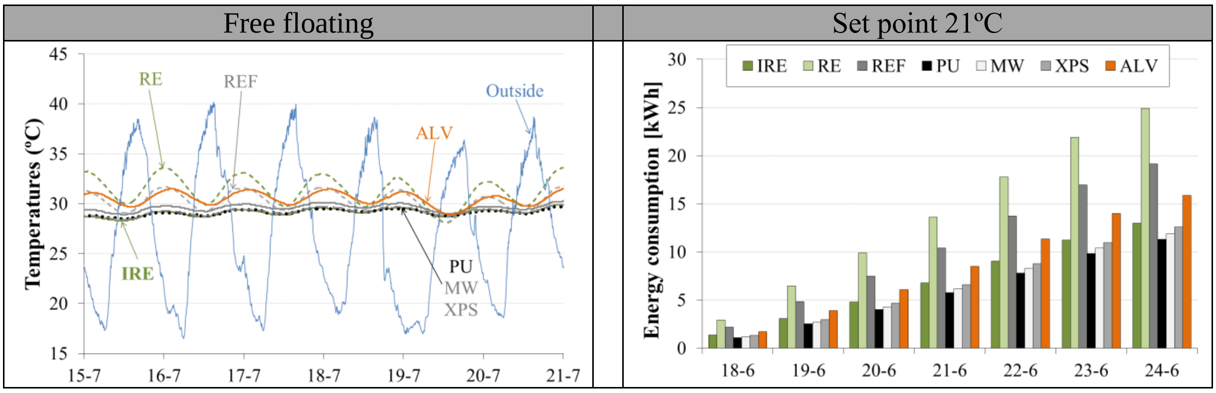


Figure 2. Results of summer experimentation.

3.2. Winter

In winter period, the thermal amplitude between daytime and nighttime were not as large as in summer (see table 1). For this reason, temperature oscillations inside cubicles are less evident in free floating conditions experimentation. Nevertheless, it can be noticed that non-insulated cubicles (RE, REF and ALV) are highly affected by the outdoor conditions at the end of the selected week when the thermal amplitude is higher. Insulated cubicles (IRE, PU, MW and XPS) kept inner ambient temperature almost constant.

In winter period, electrical energy consumption (figure 3) was very high in all cases because outdoor temperatures were all the week under the set point temperature (21ºC). When analyzing each cubicle, it can be noticed similar electrical energy consumptions between RE and REF, ALV and MW, and IRE, PU and XPS. It is important to highlight that the lowest energy consumption was registered in IRE cubicle.

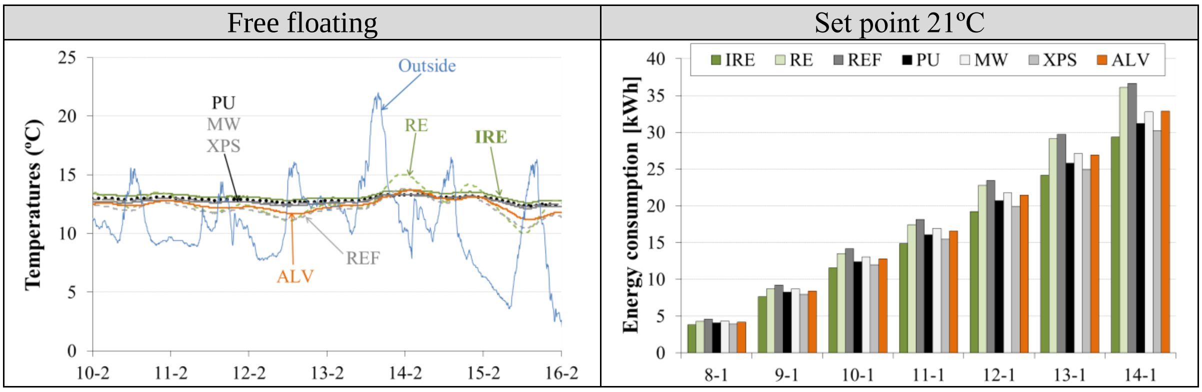


Figure 3. Results of winter experimentation.

4. Conclusions

Seven cubicles with the same inner dimensions and orientation but different construction systems are thermally tested at real experimental scale. Sustainable construction systems based on earth, wood and green roofs were used to build two of them (RE and IRE). Conventional construction systems based on clay bricks were used in the other five cubicles (REF, PU, MW, XPS and ALV). Thermal responses of cubicles are evaluated under free floating and controlled temperature conditions using a set point of 21ºC in summer and winter periods.

When analyzing temperature profiles of inner temperatures in each cubicle in free floating conditions, results show that construction systems used in walls and roofs in RE cubicle are not able to achieve good thermal response, being even worse than the REF. This means that the reduction of the wall thickness in rammed earth walls heavily penalizes its thermal behavior, especially under summer conditions and days with large thermal amplitudes.

Otherwise, when an external wooden insulation of 6 cm is added into rammed earth walls (IRE), its thermal response is notably improved. In summer season, temperature profile of IRE was very close to conventional insulated cubicles (PU, MW and XPS) in free floating conditions. In controlled temperature experiments, electrical energy consumption was also approximately the same. In winter conditions, temperature profile of IRE cubicle was also very close to conventional insulated cubicles in free floating experiments and in controlled temperature, the lowest electrical energy consumption was registered by IRE cubicle.

This paper demonstrates that similar thermal behavior can be achieved by using sustainable and environmentally friendly construction systems instead the current high embodied energy conventional ones. Therefore, it has been also demonstrated that the adaptation of rammed earth to the current constructive requirements of wall thickness and thermal response is nowadays possible.

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